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Virtual competitors influence rowers

Wellner, M ; Sigrist, R ; Riener, R

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Virtual Competitors Influence Rowers

Abstract

Highly immersive environments for sports simulation can help elucidate if and how athletes perform under high pressure situations. We used a rowing simulator with a CAVE setup to test the influence of virtual competitors on 10 experienced rowers. All participants were using the simulator for the first time. The objective was to assess the degree of presence by quantifying how the actions of the virtual competitors triggered behavioral changes in the experienced rowers. The participants completed a virtual 2000 m race with two competing boats, one being behind and one ahead of the participant. For two trials, each boat would come closer to the participant without overtaking, resulting in four experimental conditions. The behavior of the participants was assessed with biomechanical variables, questionnaires, and an interview after the race. Behavioral changes were detected with statistically significant differences in the extracted variables of oar angles, timing variables, velocities, and work. The results for biomechanical variables indicate individual response patterns depending on perception of competitors and self-confidence. Self-reporting indicated a high degree of presence for most participants. Overall, the experimental paradigm worked but was compromised by perceptive and subjective factors. In future, the setup will be used to investigate rowing performance further with a focus on motor learning and training of pressure situations.

1 Introduction

The introduction provides an insight into the fields of sports psychology, presence research, and related work with sports simulators. From this base we introduce the experimental hypotheses at the end of the section.

1.1 Factors Influencing Performance in Sports

Athletic performance depends on the level of personal fitness, individual skills, and—most prominently in competitions—on environmental conditions, including audience, competitors (Schmidt & Wrisberg, 2004), and weather. Competitors can enhance performance by adding motivation, which occurs mainly for effort-dominant tasks, or degrade performance by increasing stress, which occurs mainly for skill-dominant tasks (Lewis & Linder, 1997).

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Decreased performance related to increased stress has often been described as choking, which has been defined as the "occurrence of suboptimal performance under pressure conditions" (Baumeister & Showers, 1986), while motivational effects lead to better performance.

The influence of competitors on athletic performance has not been investigated broadly because of the obvious difficulties associated with conducting repeatable experiments in the field. Highly immersive virtual environments can address this problem, provided that they stimulate the same responses as a real competition. Understanding how pressure situations influence sports performance may also enhance training, leading to paradigms that incorporate situations that enhance performance and teach athletes to cope with situations that degrade performance.

1.2 Immersion, Presence, and Co-presence

The concepts of immersion and presence are essential to understanding interactions within virtual environments. A clear distinction between the two concepts was proposed by Slater and Wilbur (1997). While *immersion* describes the objective technological characteristics of a given system (like screen resolution, viewing angle, display size), *presence* was defined as a state of consciousness, which is related to the sense of being in a place. Research on the phenomenon of presence has mainly focused on developing presence theory and establishing methods to assess presence (Sheridan, 1992; Ellis, 1991; Slater & Usoh, 1993; Held & Durlach, 1992; Barfield & Weghorst, 1993; Barfield, Zeltzer, Sheridan, & Slater, 1995; Witmer & Singer, 1998). The common notion of presence uses a transportation metaphor, that is, "being there" (Heeter, 1992). The same notion is described by the term *place illusion*, introduced by Slater (2009) in addition to *plausibility illusion*, which refers to the "illusion that the scenario being depicted is actually occurring" (Slater). A more comprehensive definition of presence is "perceptual illusion of non-mediation" (Lombard & Ditton, 1997), which also embraces other notions of presence, namely *social presence*, the degree of "being with another" in a virtual environment (Biocca, Harms, & Burgoon, 2003).

Similar to place illusion and plausibility illusion, social presence or co-presence is conceptualized as a gradual state of experiencing the existence of other individuals—in contrast to simpler "here or not here"-concepts (Coffman, 1959). Although the main focus of social presence research has been on interaction with real people by media technology, it also covers the interactions with computer-generated agents. If virtual agents are rendered with high fidelity and show adequate behavior, they can cause emotional reactions by participants. One study investigated public speaking in front of three different types of audiences, resulting in natural reactions from the participants (Pertaub, Slater, & Barker, 2002). In environments with animated characters, the two phenomena of "social presence" and "spatial presence" coincide, thus strengthening the experience as a whole.

Since presence is a subjective experience, post-experimental questionnaires have been widely used to assess presence (Witmer & Singer, 1998; Pertaub et al., 2002; IJsselsteijn, Kort, Westerink, Jager, & Bonants, 2006; Slater, Linakis, Usoh, Kooper, & Street, 1996; IJsselsteijn, de Ridder, Freeman, Avons, & Bouwhuis, 2001). Questionnaire items are based on factors that have been identified to influence presence, for example, involvement, adaptation/immersion, sensory fidelity, and interface quality (Witmer, Jerome, & Singer, 2005).

The other major presence measurement method is to use task-specific performance as an indicator for presence. Based on the task that is specified by the virtual environment, performance metrics can be defined. General forms of these are task completion time and human performance error rate (Zhang, Fernando, Xiao, & Travis, 2006). The advantage of task-specific performance metrics is their easy integration within the software providing the multimodal environment. No additional measuring devices are needed. They also provide quantitative metrics for an unambiguous comparison of different scenarios.

The underlying assumption for using task-specific performance metrics is that presence, co-presence, and performance are related. Although it seems obvious that "some sense of presence in an environment is a necessary condition for performance to occur" (Bystrom, Barfield, & Hendrix, 1999), a clear correlation between performance and presence is difficult to validate, since there are too many factors influencing both (Nash, Edwards, Thompson, & Barfield, 2000). Some researchers have found no correlation or even negative correlation between performance and presence (Waterworth & Waterworth, 2001), but most researchers conclude that "performance may indeed be positively correlated to presence" (Sadowski & Stanney, 2002). The same conclusion can be drawn for a potential correlation between co-presence and performance (Pertaub et al., 2002; Garau, Slater, Pertaub, & Razzaque, 2005).

One major prerequisite for a highly immersive environment is natural interaction, especially for locomotion. The notion of "body-centered interaction" (Slater & Usoh, 1994) is aimed at maximizing the match between proprioception and the corresponding sensory feedback at the perceptual and cognitive level. Studies with exploratory virtual environments have confirmed this notion for walking (Slater, Usoh, & Steed, 1995; Usoh et al., 1999).

1.3 Related Work

Sport simulators are increasingly used to enhance motivation while exercising in fitness studios and at home. Numerous commercial products are available, for example, RacerMate CompuTrainer for cycling and Concept2 e-Row for rowing. Research on virtual environments for cycling has shown a positive effect of immersion on motivation and presence (IJsselsteijn et al., 2006).

In a virtual environment for rowing, a combination of biomechanical, rowing-specific variables (Kleshnev, 1998, 2002; Hill, 2002; Smith & Spinks, 1995) and subjective measures could indicate behavioral changes to a pressure situation. One earlier study was conducted with the same setup using three types of audience, inspired by a study on public speaking anxiety (Pertaub et al., 2002). But in contrast to the findings there, audience pressure resulted in few behavioral changes in rowing (Wellner, Sigrist, von Zitzewitz, Wolf, & Riener, 2010). The current study used the illusion of competitors which was supposed to create a stronger feeling of pressure and therefore more pronounced behavioral changes.

1.4 Experimental Hypotheses

1. Choking and motivational effects can be induced in a virtual environment with competitors.
2. The incidence of behavioral changes correlates with the degree of competitive pressure.
3. Competitive pressure in a virtual environment can be increased by bringing the competing boats closer to the participant, increasing the possibility of a lead change in the simulated race.

2 Methods

This section introduces the experimental setup, the participants, and the experimental design. This is followed by a description of the data collection and analysis for the behavioral variables, and the subjective measures assessed using questionnaires and interviews.

2.1 Experimental Setup

The participants sat in an immobile racing boat, which was trimmed on both sides (see Figure 1). They held one oar, which was also trimmed. The end of the oar was connected to a haptic interface (Zitzewitz et al., 2008). The participants were surrounded by three screens sized 4.44 m $\times$ 3.33 m (Figure 2). Three projectors[1] displayed a rowing scenario on these screens. The participant's head was positioned at the middle of the screen height. At the same height, a closed ring of 112 speakers and four subwoofers surrounded the participants. Using the wave field synthesis method, up to 16 sound sources could be programmed to sound as if they originated from any virtual 3D position positioned within the speaker ring.

1. Projectiondesign F3+, 5500 ANSI Lumen, resolution 1400 $\times$ 1050.

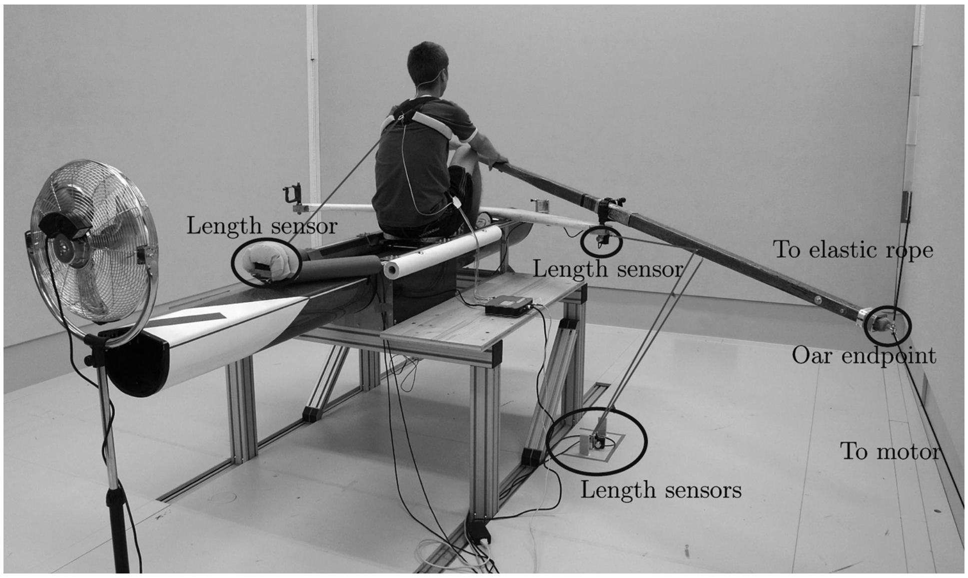

Figure 1. *Measurement setup with length sensors and mechanical components.*

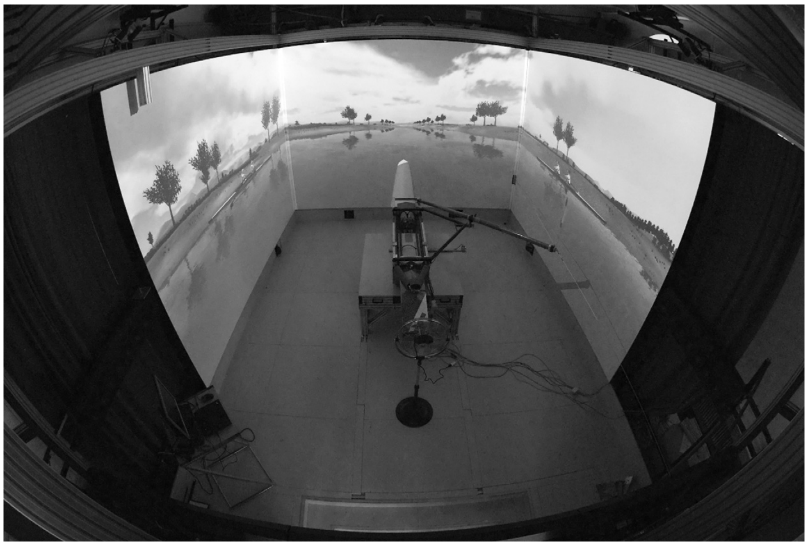

Figure 2. *CAVE setup of the* $\boldsymbol{M}^3$ *rowing simulator. The screens are visible in front; parts of the speaker ring (head height) are visible in the lower part of the picture.*

The participants saw a river scenario with water, trees, hills, sky, and competitor boats displayed on the three screens (see Figure 3). The stern of the boat was also visible on the center screen. In order to achieve realistic water behavior, we used shallow water equations, and a 2D wave simulation algorithm (Layton & van de Panne, 2002). The algorithm computed waves on a grid of 71×71 nodes, corresponding to a square area with a length of 20 m. Based on this algorithm, the participants saw propagating waves when they immersed the oar in the water and a boat trace when they advanced. In addition to waves, a water shading algorithm and moving vortex-shaped textures on top of the water were used to simulate realistic water behavior (see Figure 4).

Figure 3. *Scenario with competitors (left) and participant (right).*

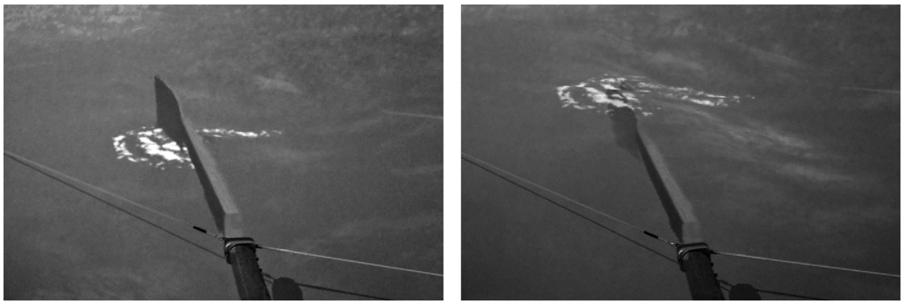

Figure 4. *Display of oar and water, oar in air (left), and immersed (right).*

Table 1. *Measured Variables*

Variable	Description
θ	Horizontal oar angle
δ	Vertical oar angle
ϕ	Rotational oar angle (turning of the blade)
F	Oar force on the oar blade rectangular to the oar
v	Boat velocity in driving direction
α	Angle of the back of the rower

The competing boats and rowers were modeled in 3D with photorealistic textures (see Figure 3). The setup achieved frame rates of more than 30 fps for all screens and conditions.

When participants immersed the oar in water, sound sources were positioned and played at the oar tip. During normal oar immersion with vertical blade alignment, one sample was played, whose volume was adjusted proportional to the relative horizontal velocity between oar blade and water. For undesired oar immersion with near to horizontal blade alignment, a splash sound was played whose volume was adjusted according to the vertical oar blade velocity. The oar splashing sounds for the competitors were implemented with one sound source per boat. The rowing sound samples were taken from a sound database.[2]

Five rope-based position sensors[3] measured distances and were used to compute the oar angles θ (horizontal), δ (vertical), and ϕ (rotation around oar axis) and to assess the seat and shoulder position (Tables 1 and 2).

The position of the seat was used to estimate each participant's head position. This estimation was based on the assumption that the participant remained seated during rowing and that the head did not change orientation with respect to the trunk orientation (rigid head-trunk connection). Therefore, the head position had two fixed

2. The Freesound Project, http://www.freesound.org
3. Micro-Epsilon, models WPS-1250-MK46 and WPS-2100-MK77.

Table 2. *Extracted Biomechanical Variables, Each Rowing Stroke Resulted in One Extracted Value*

Variable	Description
Oar angles	
θ_{Catch}	Catch angle
$\hat{\delta}_{\mathrm{Drive}}$	Maximum blade immersion during drive phase
$\hat{\delta}_{\mathrm{Recovery}}$	Maximum blade height during recovery phase
$\check{\delta}_{\mathrm{Recovery}}$	Minimum blade height during recovery phase
Timing variables	
T_{Recovery}	Duration of recovery phase
T_{Drive}	Duration of drive phase
T_{Stroke}	Duration of entire stroke
$T_{\mathrm{Drive}}/T_{\mathrm{Stroke}}$	Ratio of drive to stroke phase
$T_{\mathrm{Catch}\rightarrow\hat{F}}$	Duration between catch and maximum force
$T_{\hat{F}\rightarrow\theta=0°}$	Time difference between maximum force and $\theta = 0°$
SR	Stroke rate, frequency of the rowing movement
Seat and posture	
$\hat{s}$	Maximum seat position
$\check{s}$	Minimum seat position
$\hat{w}_{\mathrm{Drive}}$	Maximum absolute seat velocity during drive phase
$\hat{w}_{\mathrm{Recovery}}$	Maximum absolute seat velocity during recovery phase
$\hat{\alpha}$	Maximum back angle
$\check{\alpha}$	Minimum back angle
Boat dynamics	
$\bar{v}$	Mean boat velocity
$\hat{v}$	Maximum boat velocity
$\check{v}$	Minimum boat velocity
$\check{v}/\hat{v}$	Ratio between minimum and maximum velocity
$\hat{F}$	Maximum oar force
$\check{F}$	Minimum oar force
W_{Oar}	Entire work
$W_{\mathrm{Oar+}}$	Accelerating oar
$W_{\mathrm{Oar-}}$	Decelerating oar work
$W_{\mathrm{Oar+BoatDir}}$	Accelerating oar work in propulsion direction

components (height of head, boat lane) and one variable component (seat position) and was used as the camera position for the scene rendering.

A combined motor-spring system rendered forces in the horizontal direction, namely the water resistance, which was calculated as a function of the oar and seat movements (Zitzewitz et al., 2008). The maximum resistive force was applied when the oar was completely immersed with a vertical blade alignment, as expected for rowing movements. The elastic rope rendered forces in the opposite direction to the resistive forces. These occurred when an improper rowing technique was used or when the water was mistakenly touched during the recovery phase. Forces in the vertical direction were not

Table 3. *Characteristics of the Participants*

Number	Gender	Born	Level	Condition order with lane assignment
1	female	1983	international	FAST$_{\text{right}}$ SLOW$_{\text{left}}$ FAST$_{\text{right}}$ SLOW$_{\text{left}}$
2	female	1966	regional	SLOW$_{\text{right}}$ SLOW$_{\text{right}}$ FAST$_{\text{left}}$ FAST$_{\text{left}}$
3	female	1976	regional	FAST$_{\text{left}}$ FAST$_{\text{left}}$ SLOW$_{\text{right}}$ SLOW$_{\text{right}}$
4	female	1989	regional	SLOW$_{\text{left}}$ FAST$_{\text{right}}$ FAST$_{\text{right}}$ SLOW$_{\text{left}}$
5	male	1978	national	FAST$_{\text{left}}$ SLOW$_{\text{right}}$ FAST$_{\text{left}}$ SLOW$_{\text{right}}$
6	male	1982	regional	SLOW$_{\text{left}}$ SLOW$_{\text{left}}$ FAST$_{\text{right}}$ FAST$_{\text{right}}$
7	male	1982	national	FAST$_{\text{right}}$ SLOW$_{\text{left}}$ FAST$_{\text{right}}$ SLOW$_{\text{left}}$
8	male	1959	regional	SLOW$_{\text{left}}$ FAST$_{\text{right}}$ SLOW$_{\text{left}}$ FAST$_{\text{right}}$
9	male	1968	regional	SLOW$_{\text{right}}$ FAST$_{\text{left}}$ SLOW$_{\text{right}}$ FAST$_{\text{left}}$
10	male	1980	international	SLOW$_{\text{right}}$ FAST$_{\text{left}}$ FAST$_{\text{left}}$ SLOW$_{\text{right}}$

displayed. Nevertheless, participants experienced water depth because the horizontal force was dependent on the vertical rowing angle δ.

A second rower was simulated behind the participant to complete a coxless pair. This virtual rowing mate could not be seen by the participant because there was no screen behind the participant. The rowing strokes of the mate were mirrored from the participant's rowing strokes and were visible and audible to the participant.

A fan was turned on manually once participants achieved race velocity. This was intended to enhance the feeling of movement.

2.2 Participants

The participants were mainly recruited from ETH Zurich and local rowing clubs. None had used the $\mathbf{M}^3$ Rowing Simulator before. See Table 3.

Four women and six men participated (mean age 32 years, $\sigma = 9$ years). All were expert rowers with at least five years experience in rowing and all had entered competitions, although at different levels (Table 3).

2.3 Experimental Design

In the simulator, the participant first did a warm-up run of about 1000 m without competitors. This took an average time of 9:10 min ($\sigma = $ 2:07 min). After a short pause, the participant did one race of 2000 m, the classical racing distance in rowing. The instruction for the participant was to compete as if in a real race, trying to beat the competitors. The average pace of the competitors was set equal to that of the participant. In the race, all three boats started at −100 m. When the participant was ready, a prerecorded voice checked the lanes and initiated the soft start. At this soft start, the competitors were rowing with the same velocity as the participant. At 0 m, a start panel was visible and a horn sound was played to start the race.

The competitors were programmed with a distance profile, which was based on the current position of the participant $y_{\text{comp,des}} = f(y_{\text{part}})$. The competitor's distance was chosen because it correlates well with the pressure in a race situation. If the competitor was far ahead or behind, the participant was not in immediate danger of being overtaken, nor could the participant pass the leader. In discussions with experienced rowers, the critical threshold was identified as one boat length, which corresponds to a distance of 10.4 m for the coxless pair.[4] Therefore, the NEUTRAL condition was defined with one competitor about 12 m ahead and the other one about 12 m behind. Pressure was increased

4. Source: International Rowing Association.

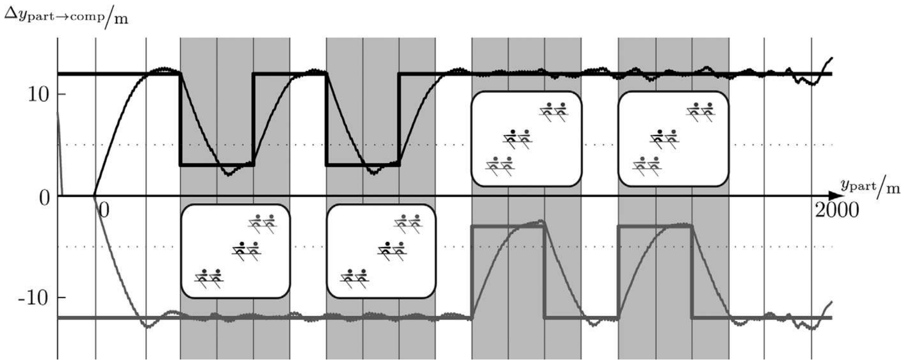

Figure 5. *Example course of a complete boat race with FAST-FAST-SLOW-SLOW order of conditions. Upper: desired (thick line) and current (thin line) distance of faster competitor. Lower: desired and current distance of slower competitor.*

by reducing the distance to a competing boat. When the slower competitor moved closer (SLOW condition), a danger of being overtaken occurred. When the faster competitor fell back (FAST condition), the participant had the possibility of overtaking. In both conditions, the competitors were programmed so as to prevent a lead change. Specifically, they remained close to the participant for 100 m of the race and then went back to the NEUTRAL position for another 100 m. With 100 m for the initial approach, each of the SLOW and FAST conditions lasted 300 m, corresponding to an average time of 1:12 min. Four test conditions ($2 \times$ FAST, $2 \times$ SLOW) were applied in each race, with five NEUTRAL conditions of 100 m separating them (Figure 5). The order of the test conditions and the assignment of the faster and slower competitor to the right or left lane followed a balanced design.

The competitors' behavior was simulated with a PI controller, regulating velocity (Figure 6). The difference Δy_c to their desired position $y_{c,des}$ was the input to the controller. The velocity of the participant was also used in the controller, because the competitors' velocity is specified relative to that of the participant. The intended behavior of the competitors was achieved with $P = 0.1$ and $I = 0.08$. The arithmetic mean of the participant's velocity was computed with 100 values, corresponding to 3 s rowing time, with an update interval of $T = 30$ ms. The participants did not know about the competitors' behavior.

2.4 Data Evaluation and Statistics

The participants started at -100 m, and the first 100 m were not analyzed. After that, the start block of 150 m followed. In this block, the competitors went ahead and behind to get to the distances of the first NEUTRAL condition. This first block of the real race was also not included for the analysis. The next 1,700 m contained the four pressure conditions ($2 \times$ SLOW, $2 \times$ FAST) and five NEUTRAL conditions in between. The last 150 m also were not analyzed because of the final spurt that rowers usually perform.

A normal distribution of the data was verified. Each experimental condition was analyzed by applying statistical tests to the three blocks of the condition itself (approaching, close, pulling away) in relation to the two surrounding NEUTRAL blocks. In order to detect statistically significant differences between blocks, we applied a one-way ANOVA to all five blocks, followed by a multiple comparison (Tukey-Kramer test with a significance level of $p < .05$). A variable had to fulfill two criteria to qualify as a reaction to a competitor condition.

1. The surrounding NEUTRAL blocks must be equal (or not significantly different).
2. At least one of the three blocks of the competitor condition must be significantly different from both surrounding NEUTRAL blocks.

In order to quantify the correlation between the number of biomechanical changes and the questionnaire

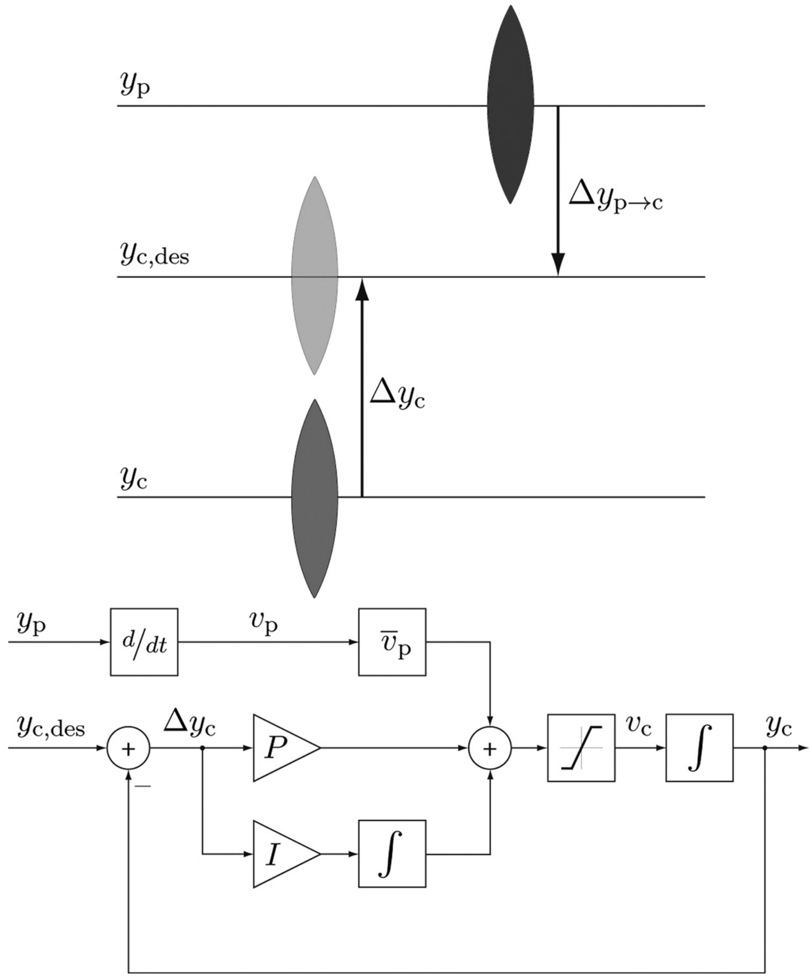

Figure 6. *Implementation of competitor behavior, v_p is the participant velocity, $\overline{v}_p$ the moving arithmetic mean (averaging window was 2 s) of the participant velocity, v_c the competitor velocity, $\Delta y_{p \to c}$ the desired distance between participant and competitor, Δy_c the distance between current and desired competitor position, and P and I are proportional and integral gain, respectively.*

scores, the correlation coefficients were determined with a 95% confidence interval.

2.5 Questionnaires and Interview

Participants completed a questionnaire on immersive tendencies before the experiment and on presence afterward (see Table 4 for sample items of both questionnaires; questionnaires adapted from Witmer & Singer, 1998). The questionnaires were analyzed according to the procedure suggested by Witmer and Singer, resulting in a number of average scores for the factors.

The investigator interviewed the participants about their personal experience in the simulator right after the virtual reality (VR) experience. Guideline questions were used (Table 5) to assess both presence and realism. The first question was about the general impression and intended to start the interview; it was not evaluated. In the interview, participants could speak without being interrupted. All interviews were recorded with a camcorder and transcribed into English.

Table 4. *Sample Items of Immersive Tendencies Questionnaire and Presence Questionnaire**

Number	Questionnaire item
Example items from Immersive Tendencies Questionnaire (Focus Subscale)	
5	Do you easily become deeply involved in movies or TV dramas?
7	How mentally alert do you feel at the present time?
8	Do you ever become so involved in a movie that you are not aware of things happening around you?
12	How physically fit do you feel today?
13	How good are you at blocking out external distractions when you are involved in something?
17	When playing sports, do you become so involved in the game that you lose track of time?
22	Have you ever gotten excited during a chase or fight scene on TV or in the movies?
28	Do you ever become so involved in doing something that you lose track of time?
Remaining subscales: general, involvement, games	
Example items from Presence Questionnaire (Auditory Subscale)	
6	How much did the auditory aspects of the environment involve you?
15	How well could you identify sounds?
16	How well could you localize sounds?
Remaining subscales: involvement/control, natural, haptic, resolution, interface quality	

*The complete questionnaires can be found at http://www.sms.mavt.ethz.ch/research/itq_pq.pdf

Table 5. *Guideline Questions for the Interview*

Number	Question
1	What was your general impression?
2	What could be improved?
3	Did you miss anything?
4	How realistic is the simulator?
5	What are the strengths and weaknesses of the simulator?
6	Who could profit from the simulator?
7	Did you get tired during the race? If so, when?
8	Did the electrodes disturb your movements?
9	Did the competing boats influence you?
10	Were the competing boats realistic?
11	Was the movement of the competitors realistic?
12	Were you influenced when the competing boats were at the same level?
13	Were you influenced when a competing boat was overtaking you?
14	Were you influenced when a competing boat was pulling away?
15	Was it motivating to catch up to a competing boat?
16	Was it motivating to pull away from a competing boat?

3 Results and Discussion

This section presents and discusses the results, beginning with the general response patterns and questionnaire scores. The section ends with a detailed presentation of three exemplary response patterns and the statistical analysis for all data.

3.1 General Results

The race times ranged from 6:49 min to 9:11 min with an average of 7:59 min ($\sigma = 0{:}45$ min). For comparison, the gold medal times for the men's and women's coxless pair at the 2008 Beijing Olympics were 6:40 min and 7:37 min, respectively. The questionnaires were completed in a couple of minutes and the interviews lasted 5:31 min on average.

All behavioral changes are displayed in Table 6, all questionnaire results in Table 7. The results of selected participants will be discussed to provide insight into the most common response patterns.

3.2 Individual Discussion on Participants

Participant 1 showed behavioral changes in the biomechanical variables for all four conditions. These changes are most clearly visible in the amount of maximum force (Figure 7). The first three conditions show a significant increase in the maximum force according to the criteria defined earlier (Section 2.4). Note that a trend in the fourth condition prevents the visible force increase from becoming significant, because the surrounding NEUTRAL blocks are significantly different. The questionnaire scores (Table 7) were high for both the Immersive Tendencies Questionnaire and the Presence Questionnaire, compared to the other participants. In the interview, the participant reported a high degree of presence in the simulator. On the question of whether she was brought back to her immediate surroundings at the end of the simulation, she responded,

> When I put away the oar after the finish, I realized that the boat was not moving at all. I would say, I was not completely in this world, but it was easy to get immersed.

She also noted that the competitors were not getting slower although she tried hard to attack them.

> Concerning the competitors, I attacked the faster one twice, once at 400 m, a second time at 900 m. I was really getting closer, but they just pulled away. They didn't subside. And according to my experience, everybody subsides at a certain point when attacked twice.

Participant 5 showed one clearly discernible burst at 1000 m, apart from the start and finish bursts, which were not included in the analysis (Figure 8). The 1000 m burst started in a NEUTRAL block. The participant scored lowest in both questionnaires, compared to the other participants. In the interview, the participant reported a low degree of presence.

> If you are more serious with it, one can feel in the race. But I had always the impression that the other boat had been programmed on the distance. . . But actually you can feel like being in the race, if you improve the whole thing.

He reported the different force curve as the main difference from real rowing.

> What have been the main differences, compared to real rowing?—The force curve. In the stroke phase, the force is not constant, rather decreasing at the end. You can start as you like, there is some force, but it's not right, I don't have the right feeling, either I catch really or I'm pulling in the air. There is no real differentiation. In the middle you have a good amount of force and you really pull, but then you are swinging out too much, because the force is decreasing.

It is important to note that we had to limit the force for technical reasons. And the participant was very strong (1.88 m tall, sturdy) and could therefore generate high forces, reaching the simulator's force limits repeatedly. This explains the perceived gap between simulation and real rowing.

Table 6. *All Statistically Valid Behavioral Changes in the Biomechanical Variables*

Variable	Participant identification 1	2	3	4	5	6	7	8	9	10	Σ_{Var}
Oar angles											
θ_{Catch}	↓···	·↑··	···↑	··↑·	····	···↓	····	····	····	↓···	6
$\hat{\delta}_{\text{Drive}}$	···↑	····	····	····	····	····	····	··↓·	····	····	3
$\hat{\delta}_{\text{Recovery}}$	····	·↓··	····	····	····	····	····	····	····	····	1
$\check{\delta}_{\text{Recovery}}$	····	··↓·	····	····	····	····	····	····	····	··↓·	2
Timing variables											
T_{Recovery}	··↓·	····	··↓·	····	····	····	····	····	·↑··	·↑··	4
T_{Drive}	·↓↓·	↑···	····	·↑·↓	··↓·	····	····	····	····	↓···	7
T_{Stroke}	····	····	··↓·	↓···	··↓·	····	↑···	····	·↑··	·↕··	6
$T_{\text{Drive}}/T_{\text{Stroke}}$	····	····	····	····	···↑	····	··↓·	····	↓···	···↑	4
$T_{\text{Catch}\rightarrow F_{\text{Max}}}$	↓↓··	····	····	····	··↓·	···↑	····	·↑··	·↓··	····	6
$T_{\hat{F}\rightarrow\theta=0^\circ}$	····	····	····	····	··↓·	····	····	····	····	····	1
SR	····	····	··↑·	↑···	··↑·	····	↓···	····	····	·↕··	5
Seat and posture											
s_{Max}	↓···	····	····	····	····	····	··↓·	····	↓···	·↓·↓	5
s_{Min}	···↑	····	····	····	····	····	····	····	····	·↑··	2
$\hat{w}_{\text{Drive}}$	····	····	····	··↓·	····	····	↑·↑·	····	····	·↑··	4
$\hat{w}_{\text{Recovery}}$	····	····	····	····	··↓·	····	····	····	····	····	1
Boat velocity, force and work											
$\hat{\alpha}$	↑···	··↑·	·↑··	··↓·	····	···↑	····	····	····	·↑·↑	7
$\check{\alpha}$	↑↑··	····	····	····	····	····	····	····	····	····	2
$\bar{v}$	····	····	·↑··	····	··↑·	↑↓··	↓···	····	↓↓··	·↓··	8
$\hat{v}$	····	····	··↑·	····	··↑·	↑···	↓···	···↓	↓↓··	·↓··	8
$\check{v}$	····	····	····	····	··↑·	····	↓···	·↓··	↓↓··	·↓··	6
$\check{v}/\hat{v}$	····	↓···	····	····	····	··↓·	····	·↓··	····	····	3
$\hat{F}$	↑↑↑·	····	····	····	····	··↑·	····	····	····	·↑··	5
$\check{F}$	····	····	····	····	····	··↓·	↑···	····	·↑··	·↓··	4
W_{Oar}	····	····	·↑··	·↑··	··↑·	↑↓·↑	····	····	↓↓··	·↓··	9
$W_{\text{Oar+BoatDir}}$	↑···	↓···	····	··↓·	····	··↑↑	↓···	····	····	····	6
$W_{\text{Oar+}}$	↑···	····	····	··↓·	··↓·	··↑↑	↓···	····	····	·↑··	7
$W_{\text{Oar−}}$	·↑··	····	····	····	····	··↑·	↓···	····	····	·↑··	4
Conditions	F|S|F|S	S|S|F|F	F|F|S|S	S|F|F|S	F|S|F|S	S|S|F|F	F|S|F|S	S|F|S|F	S|F|S|F	S|F|F|S	
Σ_{Cond}	8|5|3|2	3|2|2|0	0|3|4|1	2|2|5|1	0|0|11|1	3|2|6|6	10|0|3|0	0|3|1|1	6|8|0|0	2|15|1|3	
Σ_{Subj}	22	11	9	13	16	22	14	5	14	21	

Table 7. *Questionnaire Results, Answer Scales Were from 1 to 7; ITQ: Immersive Tendencies Questionnaire; PQ: Presence Questionnaire*

Variable	1	2	3	4	5	6	7	8	9	10	$\bar{x}$
ITQ_{Focus}	5.6	3.1	5.1	6.0	4.0	3.9	5.3	4.9	4.4	5.0	4.7
$ITQ_{Involvmt}$	5.6	3.9	5.4	4.3	1.9	4.3	5.0	3.4	2.7	4.0	4.0
ITQ_{Games}	3.0	1.0	3.0	1.0	1.0	6.0	3.5	3.5	3.5	6.5	3.2
ITQ_{Total}	4.9	3.6	4.8	4.6	3.2	4.3	4.9	3.9	3.7	4.2	4.2
$PQ_{Inv/Ctrl}$	5.6	5.2	5.3	5.1	4.4	5.3	5.1	4.6	6.0	5.4	5.2
$PQ_{Natural}$	6.0	3.5	5.0	5.5	4.5	5.0	5.0	5.0	6.0	5.0	5.0
$PQ_{Sensory}$	5.0	5.0	6.0	6.0	6.0	7.0	5.0	4.0	7.0	5.0	5.6
$PQ_{Auditory}$	6.0	4.7	5.3	6.0	5.0	5.3	3.3	1.7	6.7	4.0	4.8
$PQ_{Distractn}$	5.3	6.0	6.3	5.5	4.8	6.8	4.5	5.8	5.3	4.8	5.5
$PQ_{Realism}$	5.0	3.0	4.0	5.0	3.0	3.5	4.0	2.0	3.5	3.5	3.6
PQ_{Haptic}	6.5	6.0	4.0	5.5	2.5	4.5	4.5	4.5	6.0	6.0	5.0
$PQ_{Resolutn}$	6.0	5.0	5.5	6.0	6.0	5.5	6.0	4.0	6.5	4.0	5.5
$PQ_{IF\ Quality}$	6.0	7.0	6.0	7.0	7.0	7.0	4.0	6.5	6.5	5.5	6.3
$PQ_{Control}$	4.0	1.0	5.0	7.0	4.0	3.0	4.0	5.0	4.0	4.0	4.1
PQ_{Total}	5.6	5.0	5.3	5.5	4.6	5.4	4.7	4.5	5.8	4.9	5.1

Participant 8 showed practically no behavioral changes. This fits the answers he gave in the interview and fits the low scores of the presence and immersive tendency questionnaire (PQtotal $=$ 4.5, ITQtotal $=$ 3.9). He did not feel that he was in the race, and he was not aware of the behavior of the competitors.

> No, I would not say that I was in the race. Somehow, a certain element of a race was missing. It was a simulated race. . . . I can't say what is missing. . . . It was to 95% realistic. . . . I never made a burst. I did not have the feeling that the competitors did a burst.

Overall, the majority of participants showed reactions to part of the pressure conditions with very individual response patterns. About one third did not react in a clear way and one participant (participant 5) followed his personal race strategy, regardless of the competitors' behavior.

3.3 Correlation Analysis

The correlation coefficients were determined between Immersive Tendencies Questionnaire total score (ITQ), Presence Questionnaire total score (PQ), and number of significant changes in the extracted biomechanical variables (BC). The results were

$-r = 0.32$ ($p = 0.37$) for ITQ/PQ (medium correlation)

$-r = 0.18$ ($p = 0.62$) for ITQ/BC (small correlation)

$-r = 0.35$ ($p = 0.32$) for PQ/BC (medium correlation)

The two questionnaire scores show a medium correlation. This means that participants with a high score in the Immersive Tendencies Questionnaire are also likely to have a high score in the Presence Questionnaire. The same level of correlation was found for the Presence Questionnaire and the number of behavioral changes. This is an indication for a relationship between presence/co-presence and performance. Interestingly, the correlation between Immersive Tendencies Questionnaire and behavioral changes was small.

Overall, the low number of participants and the medium levels of correlation do not allow a well-founded conclusion. The results show tendencies that endorse the hypotheses.

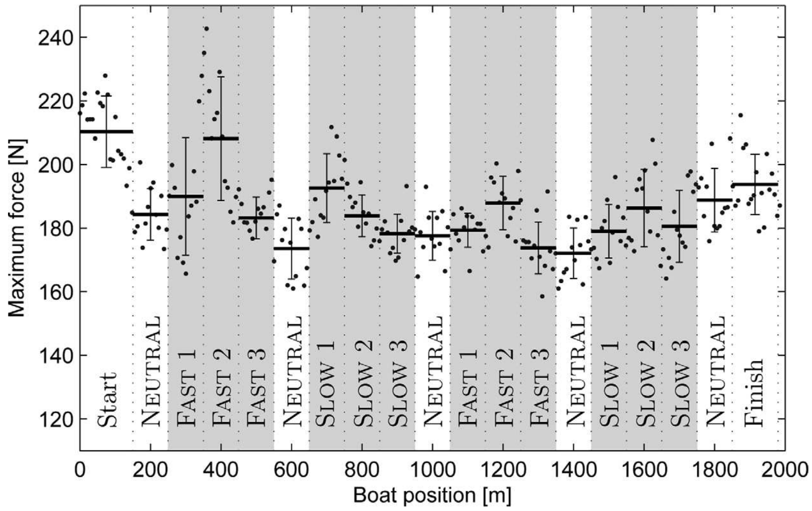

Figure 7. *Maximum force during stroke for participant 1.*

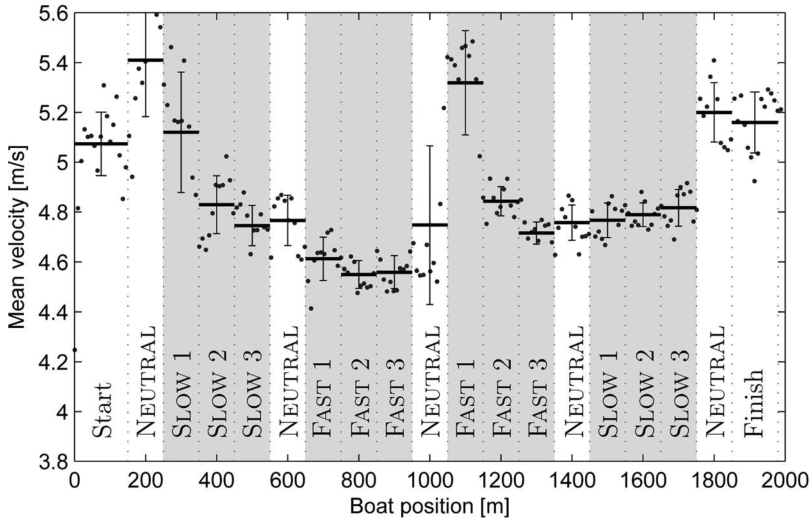

Figure 8. *Mean velocities of participant 5.*

4 Conclusions and Future Work

This section provides conclusions on some common response patterns. Further on we revisit the experimental hypotheses and elaborate on lessons learned. Lastly, future work will be outlined.

4.1 Spatial Presence and Co-presence

Analyzing the average scores of the presence questionnaire, the two factors of realism and control scored lowest (out of 10 factors overall). If we apply the distinction between place illusion and plausibility illusion (Slater, 2009), the two low-scoring factors can be attributed to the plausibility component, whereas the other factors, auditory quality, interface quality, sensory, distractions, involvement/control, and resolution, are attributed to the place illusion. Therefore, the participants experienced a high degree of place illusion but a lower degree of plausibility illusion. The postexperiment interviews confirm this assumption. Most critical comments concerned the plausibility of events (missing boat tilting, unrealistic oar force, rolling start).

The behavior of the competitors was also criticized, relating to the degree of co-presence of the simulation. Some participants realized that they could not beat the competitors and some focused on their own race without noticing the competitors at all. But all accepted the race situation and rowed as hard as they could. Without competitors, the race situation would not have been plausible, therefore co-presence contributed to the plausibility illusion.

4.2 Influence of Competitors' Lane and Speed

The experimental FAST conditions triggered more changes in the biomechanical variables than the SLOW conditions. Although the number of variable changes is not an exact metric, the trend is still remarkable. To explain this difference, the participant's perception of the competitors must be considered. Most participants did not judge the slower boat to be a threat, hence their attention was directed on the faster boat to a greater degree.

There was also an influence of the competitors' sides. More variable changes occurred for competitors on the right side (participant viewing direction). This trend can be explained by a fixation on the single oar on the port side (to the right, in the figure) of the boat. This could cause an attentional bias to the right side, leading to more reaction to competitors on the right. It must be noted that no participant could report the slower and faster competitors' behavior comprehensively, and that one boat could be overlooked if the attention of the participant was directed to the other side.

4.3 Review of Experimental Hypothesis

The hypotheses under investigation were:

1. Choking and motivational effects can be induced in a virtual environment with competitors.
2. The incidence of behavioral changes correlates with the degree of competitive pressure.
3. Competitive pressure in a virtual environment can be increased by bringing the competing boats closer to the participant, increasing the possibility of a lead change in the simulated race.

Overall, the hypotheses worked for part of the participants and for part of the experimental conditions. The "loss" occurred at two stages, subjective attention and decision.

1. Does the participant perceive the relative movement of the competitor (either attacking or falling back)?
2. Does the participant decide to react to the relative movement?

The decision to react to the competitor's movement is based on self-confidence and previous experience in race situations.

The assessment of presence by monitoring behavioral changes in response to competitor moves was only partly successful. One reason was that participants—although being present—may have not seen the competitor move or may have decided not to react. A second problem is that the exact time of reaction is unclear, as different participants may judge a different distance of the competitor as threatening. Although other methods with more pronounced events like breaks in presence (Garau et al., 2008; Slater et al., 2006) may be better suited to assess presence, a natural and intuitive integration of the presence assessment method remains the major challenge of the field.

4.4 Lessons Learned

The main lesson from this study was that the combination of behavioral, task-specific measures, questionnaires, and an interview proved successful and sufficient to observe and record a broad range of response patterns. We previously assessed the use of psychophysiological variables in a similar study with a virtual audience (Wellner et al., 2010), but we found that these variables responded more to exercise than to psychological changes.

Using an adapted version of the Witmer and Singer questionnaires worked well for our experiment. The noninformative section of the questionnaire was the video gaming subscale. Video games are less common in Switzerland than in the United States. Therefore, this questionnaire could be shortened for countries with a similar low prevalence of game consoles.

A more realistic simulation of competitor behavior may increase the plausibility illusion in our virtual environment. The approach worked quite well for most of the participants, although some reported that many professional rowers try to pull away at 1000 m and at the end of the race. With the aim of a balanced design and multiple observations in mind, we had to program several zones where competitors pulled away or fell back. The behavior was also independent of the performance of the participant, to guarantee similar conditions.

The mixed reality setup with a real boat and oar, surrounded by screens, motors, and boxes, proved very successful for the simulation of rowing. The clear advantage of the simulator is the haptic interaction via the rope robot. Most participants were fascinated by the quality of the simulation and confirmed that we made the right technology choices, resulting in a sophisticated tool that is suitable for rowing race simulations.

4.5 Future Work

After the promising results of this pilot study, an extended study with more participants is needed to investigate the effect of competing boats in more detail. Slight modifications in the experimental design could include improved competitor behavior. The overall setup is under constant development, therefore the haptic interaction can be improved to match real rowing more closely. It might also be interesting to focus on special groups, for example, rowers who have a known problem with pressure or race situations in real life. Another issue of exploration could be the sensitivity of the rowing movement. Tests with alternative, strong pressure conditions, for example by introducing motivating or choking elements depending on motor performance, could give insight into the sensitivity of the rowing movement.

In addition to investigations of the presence phenomenon, the developed system also could be used to study optimal rowing patterns and to assess the influence of feedback on rowing performance. One idea is to create a virtual trainer, which continuously analyzes the performance and provides adequate feedback. This would be a closed loop to improve the rowing technique.

Experienced rowers could use a machine like this to get detailed feedback on race technique and on susceptibility to pressure conditions. This could help them to further improve their technique, prepare a competition, or train without their trainer.

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